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J. Huang

W. M. Hess

D. J. Weber

A. E. Purcell

C. S. Huber

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SCANNING ELECTRON MICROSCOPY: TISSUE CHARACTERISTICS AND STARCH GRANULE VARIATIONS OF POTATOES AFTER MICROWAVE AND CONDUCTIVE HEATING

J. Huang[1], W.M. Hess[1], D.J. Weber[1], A.E. Purcell[2], and C.S. Huber[2]

[1]Department of Botany, [2]Department of Food Science and Nutrition,
Brigham Young University, Provo, UT 84602 USA

Abstract

In order to determine cytological effects of microwave heating compared to conductive heating, whole potatoes were heated in a microwave oven in plastic bags for 0.5, 1 and 2 minutes and in boiling water for 5, 10 and 20 minutes. Both heating treatments caused swelling and partial disruption of starch granules. However, as observed with scanning electron microscopy, swelling patterns of starch granules were different in potatoes using the two heating processes. In conductive heating potatoes were heated from the outside to the inside. Microwave heated potatoes were heated fairly uniformly in different regions of tubers. The weight loss of potatoes was insignificant with both heat treatments. The softening of potatoes heated in boiling water corresponded with conductive heating patterns. With both conventional heating and microwave heating potatoes were softer outside than inside, although this pattern did not correspond with heating patterns with microwave heating.

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Direct inquiries to W.M. Hess
Telephone number: 801 378 2451

KEY WORDS: Scanning electron microscopy, starch granules, microwave heating, conductive heating

*Address for correspondence:
W.M. Hess, Electron Optics Laboratory
129 WIDB, Brigham Young University
Provo, UT 84602 USA
Phone No. (801)378-2451

Introduction

The use of microwave energy for processing and cooking foods has increased greatly in recent years. Microwave heating offers rapid and economic methods for processing food products of high organoleptic and nutritional value. Heating that occurs as a result of microwave energy is caused by molecular vibration in foods. Therefore, microwave energy has a much greater penetration depth than the heat produced by conventional methods (Knutson et al., 1987). In food applications microwave energy penetrates to the center of the food in a relatively short time and heats the food quickly. In terms of energy cost differentials, industrial microwave food processing has become more economically attractive in recent years, as costs of gas and oil have risen and use of coal and nuclear energy sources for generating electrical power has increased (Mermelstein, 1989).

Although many acceptable food products are produced by microwave energy, less satisfactory results are obtained with some starch-based foods. The reason for this may be related to fast heating rates, difference in heat and mass transfer mechanisms, or specific interaction of the components of the food with microwave radiation (Goebel et al., 1984).

Today, potatoes provide 25% of the world's food from plants and play a major role in the diet of many people. Few studies have been conducted on the effects of microwave heating on starches of potato. Collison and Chilton (1974) found that microwave-heated samples of potato starch were damaged more rapidly than forced air convection-heated samples. They also suggested that the starch:water ratio was more important than heating rate in determining the extent of damage. Goebel et al. (1984) studied starch granule swelling over a range of water levels commonly found in starch-based food systems and developed a classification of the stages of granule swelling. They indicated that at each starch:water ratio the range of stages of swelling and matrix development was smaller in convection-heated samples than in microwave-heated samples, but the convection-heated samples

were at more advanced stages of gelatinization than the comparable microwave-heated samples.

Chen et al. (1971) studied textural changes of the potato tissue caused by heat. When the temperature of a potato is raised above 50C, starch granules start to swell and begin to gelatinize at 64-71C. This process results in cells becoming less angular and in cell separation. Sogginess of the tissue may also occur (Roberts and Proctor, 1955). Reeve (1954) reported that upon prolonged heating, the hemicellulose and cellulose components undergo some breakdown. Collins and McCarty (1969) observed that microwave energy produced comparable softening in about one-third the time required by boiling water. They also reported that a sensory panel was unable to distinguish significant differences in texture between potatoes cooked in water and by microwaves. Preliminary observations indicated that the microwave-cooked potatoes might possess a more mealy texture.

Different heating patterns with microwave heating have been reported by several researchers. Chen et al. (1971) conducted heating studies on whole white potatoes with microwave energy (1 kW at 2450 MHz) and boiling water, using white potatoes with a mean radius of 1.95 cm and a mean weight of 29 g. When temperature measurements were made after various treatment durations, a temperature gradient from core to periphery was observed with microwave heating which was opposite to the gradient for heating in boiling water. Later Ohlsson and Risman (1978) carefully studied temperature distribution in spheres and cylinders of potatoes heated with microwave energy. They found more pronounced core heating at 2450 MHz in spheres with diameters in the 2- to 6- cm range. However, earlier work by Collins and McCarty (1969), in which microwave energy was compared with boiling water, indicated a temperature gradient from the surface to the core instead of the core to the surface shown by Chen et al. (1971) and Ohlsson and Risman (1978). It is difficult to generalize across a number of studies in which heating conditions are different.

Physical properties of foods are very often correlated with their microscopic structure. The purpose of this study was to determine swelling patterns of starch granules and heating patterns of potatoes during microwave and conductive heating. Scanning electron microscopy (SEM) was used to characterize changes in potato starch granules during microwave heating and conductive heating.

Materials and Methods

Raw Potatoes

Russet potatoes were selected from a commercial supplier. Whole potatoes with uniform size, mean radius (5.8-6.1 cm) and mean weight (117-162 g), were used.

Conductive Heating Process

Whole potatoes were heated in boiling water according to the stages listed in Table 1. Temperatures at the center, side, and end regions of potatoes were measured with a DM 302 series thermocouple. Iron constantin thermocouples were inserted so that one was at the mass center of the potato, one at 2-3 mm deep at one end and another at 2-3 mm on the side. Heating experiments were replicated four times

Temperatures were recorded every minute during the heating process. After heating, samples were cooled immediately with running tap water. Tissues from the center, side, and end regions of each conductive-heated potato were chosen as representative regions of potatoes for SEM studies.

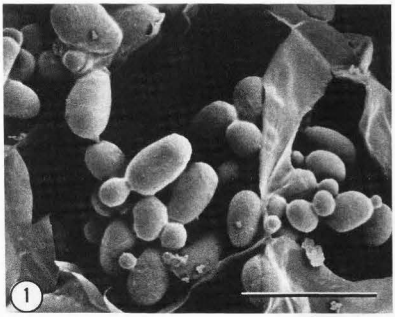


Fig. 1. Starch granules in raw potatoes. Bar = 100 μm.

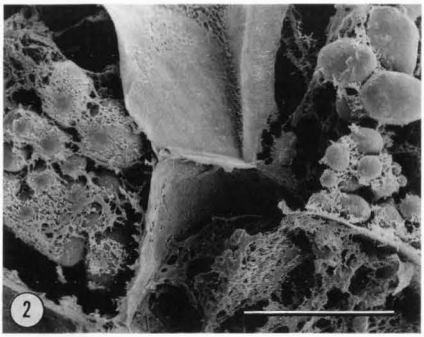
Table 1. Temperature and Heating Time of Each Stage During Treatments

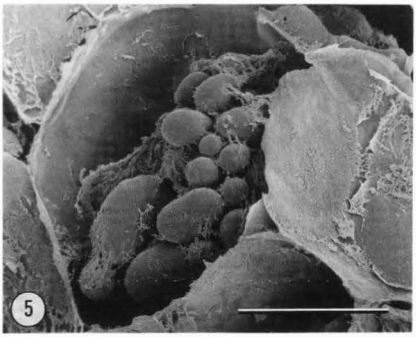
	Boiling Water		Microwave	
Stage[1]	Center temp. °C	Heating time minutes	Center temp. °C	Heating time minutes
1	46	5	38	0.5
2	65	10	66	1
3	90	20	80	2

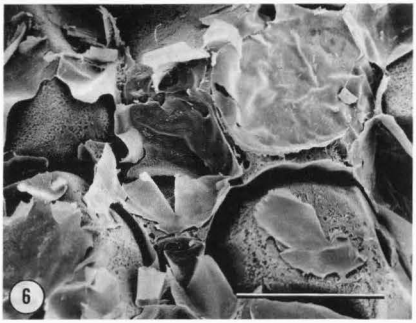
[1]Stages:
1. Center of potatoes heated to temperatures which are below their starch gelatinization.
2. Center of potatoes heated to temperatures where starch gelatinizes.
3. Center of potatoes heated to temperatures which are above starch gelatinization.

Fig. 2. Center region of boiled potato sample heated to 46C. Fig. 3. Side region of boiled potato sample heated to 46C. Fig. 4. End region of boiled potato sample heated to 46C. Fig. 5. Center region of boiled potato sample heated to 65C. Fig. 6. Side region of boiled potato sample heated to 65C. Fig. 7. End region of boiled potato sample heated to 65C. Bar = 100 μm.

Potato starch granules







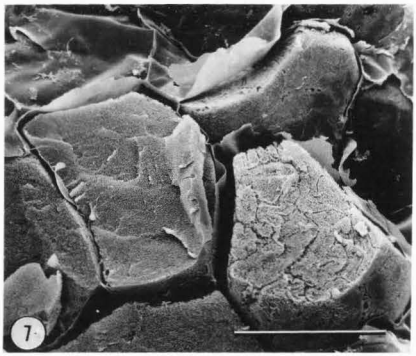


Table 2. Characteristics of Progressive Gelatinization of Boiling Potatoes

Stage	Center Region	Side Region	End Region
1	mostly individual small grains	clumped small granules	large clustered granules filled whole cell
2	small to medium clumped granules	large swollen granules	large swollen granules
3	swollen granules with reticulated structure	swollen granules with reticulated structure	swollen granules with reticulated structure

Table 3. Characteristics of Granulation of Microwave and Treated Potatoes

Stage	Center Region	Side Region	End Region
1	small individual granules	small clumped granules	small clumped granules
2	clustered large granules filled whole cell	large swollen starch granules, individual granule no longer visible	large swollen starch granules
3	large swollen starch granules	large swollen starch granules	large swollen starch granules

Sampling and Microwave Heating Process

Whole potatoes were placed in plastic bags and heated in the center of a microwave oven according to the stages listed in Table 1. The microwave oven was operated at 2450 MHz frequency. Immediately after heating, thermocouples were inserted as in conventional heated potatoes. Temperatures at the center, side, and end regions of each sample were measured at 30 second intervals until the temperatures at the center began to decrease. Samples were then quickly cooled with running tap water. Tissues from the center, side, and end regions of microwave heated potatoes were chosen as representative regions of potatoes for SEM studies. Heating experiments were replicated four times.

Preparation For SEM

After processing, samples from representative regions of potatoes, including the unheated control, were frozen in liquid freon followed by liquid nitrogen before being fractured with razor blades. Fractured samples were then freeze-dried 12-24 hours. The temperature of the condensing plate was -65C. The dry samples were mounted on aluminum stubs and a modified Polaron E5300 freeze-drier was used to gold sputter samples. The fractured surfaces of samples were examined with an JEOL 840A SEM.

Water Loss and Hardness Measurement

Potato samples were weighed before and after heat treatments so that water loss could be measured. Firmness of the heated potatoes was measured by use of a Voland-Stevens-LFRA Texture Analyzer using a 1.6 mm diameter stainless steel plunger. The plunger was positioned to penetrate to the center of potatoes at a right angle to the surface. Force (kg/cm^2) required to penetrate into the center of each potato was recorded as hardness. Travel speed of the plunger was 0.5 mm/sec.

Results

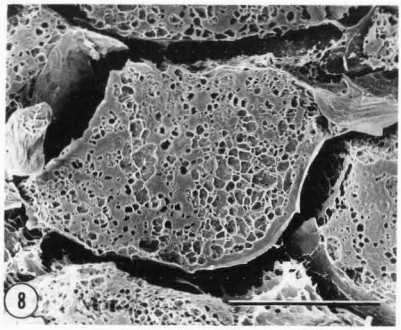
Unheated Control Samples

Starch granules in unheated potatoes were smooth and small and were not fused (Fig 1). Individual granules were distinct.

Swelling Pattern of Conventional Heated Samples

Representative regions from each stage are shown in Figures 2-10 and the characteristics of each region at every stage are summarized in Table 2. In Stage 1 (Figures 2-4) starch granules progressively clumped and were swollen at the edges of potatoes. Figures 5-7 show that at Stage 2 coalescence occurred only in outer regions of boiled samples while a considerable number of unswollen starch granules was still present in the inner region. Figures 8-10 show that for Stage 3 all the starch granules were swelled. In the center region the starch was coarsely reticulated (Fig. 8). In the side region, where temperatures were higher, the reticulation was finer (Fig. 9). In the end region, where temperatures were near boiling temperatures, the cell contents were homogenous (Fig. 10). In summary, gelatinization first occurred in end regions of stage 1, and advanced until it reached stage 3 where most of the starch appeared to be gelatinized. Separation of adjacent cell walls did not occur even after boiling the potatoes for twenty minutes in stage 3.

Fig. 8. Center region of boiled potato sample heated to 90C. Fig. 9. Side region of boiled potato sample heated to 90C. Fig. 10. End region of boiled potato sample heated to 90C. Fig. 11. Center region of microwaved potato sample heated to 38C. Fig. 12. Side region of microwaved potato sample heated to 38C. Fig. 13. End region of microwaved potato sample heated to 38C. Bar = 100 μm.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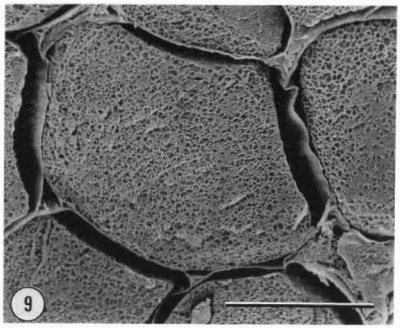
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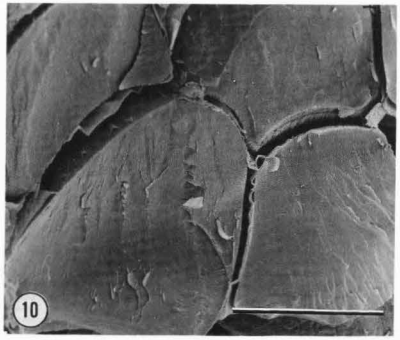
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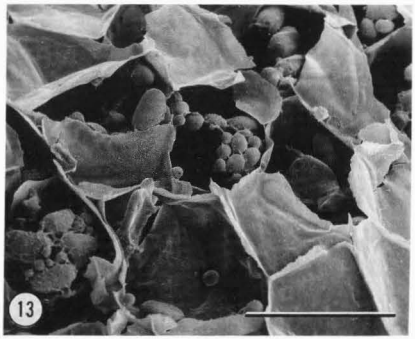
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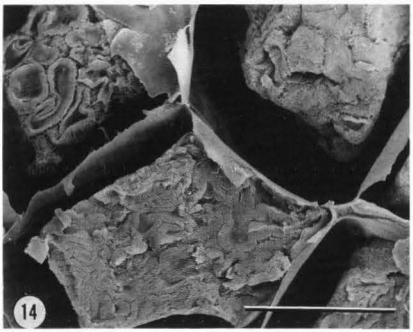
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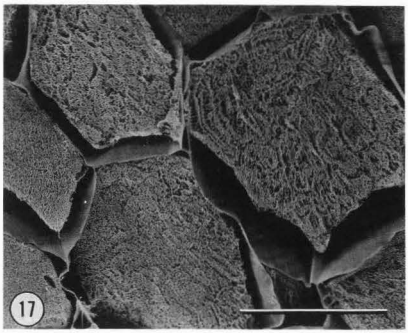
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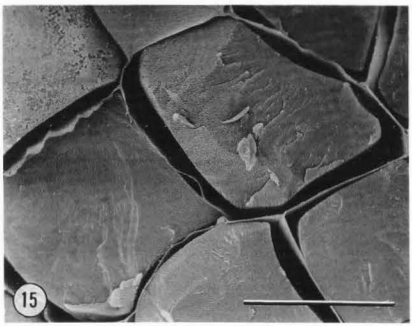
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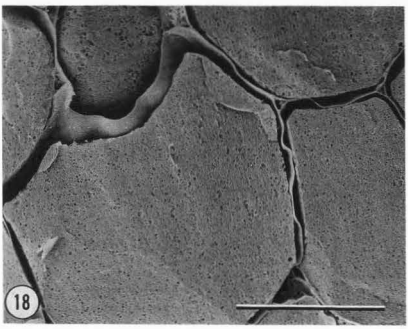
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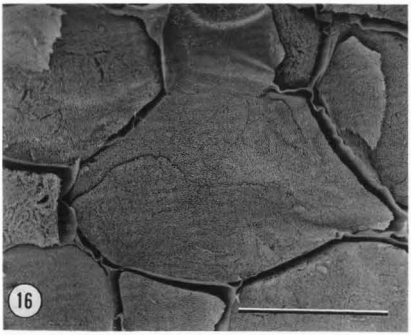
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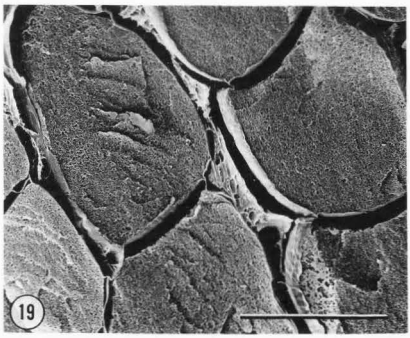
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Table 4: Weight Losses of Treated Potatoes

Temperature (°C)	Weight (g) Before Treatment	Weight (g) After Treatment
Conventional Treated		
40	179	179
62	185	185
90	178	177
Microwave Treated		
41	192	191
62	199	192
82	200	191

Swelling Patterns of Microwave Heated Samples

Representative regions of microwave treated samples from each stage are shown in figures 11-19. The characteristics of each region at each stage are summarized in Table 3. No granulation occurred in stage 1 (Figs. 11-13). However, the small unswelled granules appeared to be different from the original unheated sample. The granules in this stage started to clump.

In stages 2 and 3 (Figures 14-19) coalescence of starch grains occurred in both inner and outer regions of the microwave samples. The whole potato appeared to be evenly gelatinized at these stages and irregular shaped granules filled the whole cells in both the outer and inner regions of potatoes. In addition there were large intercellular spaces in the samples.

Heating Patterns

The time-temperature profiles for the boiling water and microwave treated samples are shown in Figs. 20-23. With microwave heating, shorter times (approximately ten times shorter) were required for the potato starch to reach gelatinization temperatures in the center of potatoes.

There was a significant difference in time-temperature profiles between microwave and conductive heating. During conductive heating the temperature of boiled samples was higher in peripheral potato tissues. The temperature of peripheral regions of potatoes reached about 90 C within one to two minutes when put into boiling water and remained at this temperature throughout the heating, while the temperature in the center regions of potatoes increased slowly to 90C. (Figs. 20-22). On the other hand, microwave heating temperatures were fairly uniform in different regions of tubers (Fig. 23).

Fig. 14. Center region of microwaved potato sample heated to 66C. Fig. 15. Side region of microwaved potato sample heated to 66C. Fig. 16. End region of microwaved potato sample heated to 66C. Fig. 17. Center region of microwaved potato sample heated to 80C. Fig. 18. Side region of microwaved potato sample heated to 80C. Fig. 19. End region of microwaved potato sample heated to 80C. Bar = 100 μm.

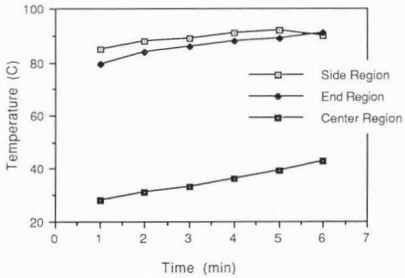

Fig. 20. Penetration of heat into potato treated by boiling water during stage 1.

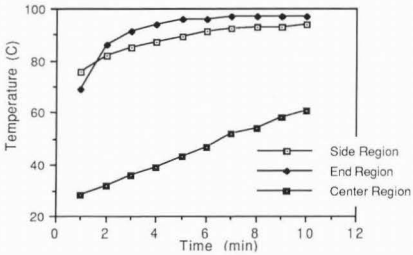

Fig. 21. Penetration of heat into potato treated by boiling water during stage 2.

Weight Loss and Texture of Treated Potatoes (Microwave versus Boiling Water)

The weight loss (Table 4) of potatoes, for the most part, was insignificant with both treatments. However, the weight loss of microwave treated potatoes was more evident than with the boiling water treated potatoes (Figs. 24-25).

The hardness of raw potatoes and treated potatoes is shown in Figs. 26-28. The hardness of boiling water heated potatoes increased from the outside layer to the inside layer. The hardness of the center part did not decrease until the center part was heated to gelatinization temperatures (Fig. 27). With raw potatoes (Fig. 26), boiling water heated potatoes (Fig. 27), and microwave heated potatoes (Fig. 28) the skin offered resistance to penetration. Once the skin was penetrated, stress depended upon the hardness of the tissue. The softest point of the tissue was evident by the minimum values on the stress/depth curves (Fgis. 26-28).

The hardness of microwave heated potatoes stayed at about the same level at stage 1 while the hardness at stages 2 and 3 increased from the outside to the inside as was observed with the boiling water treated samples (Fig. 28). The

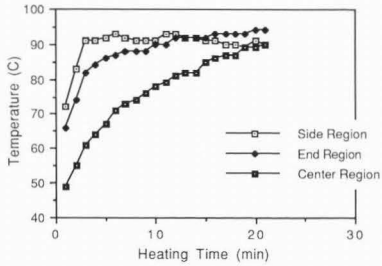

Fig. 22. Penetration of heat into potato treated by boiling water during stage 3.

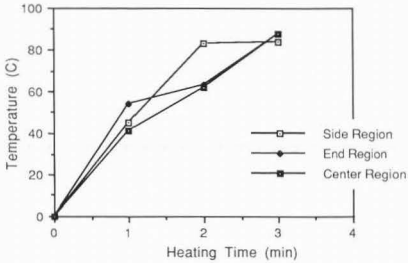

Fig. 23. Penetration of heat into potato treated by microwave during stage 1, 2, and 3.

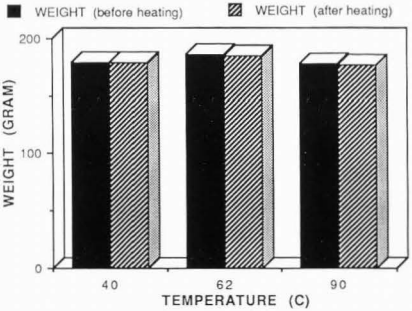

Fig. 24. Weight loss of potatoes during boiling water heating.

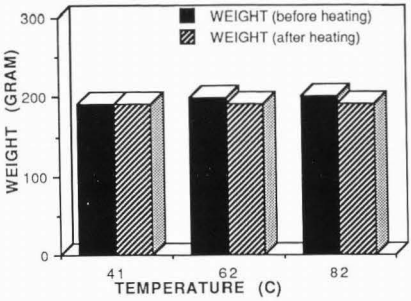

Fig. 25. Weight loss of potatoes during microwave heating.

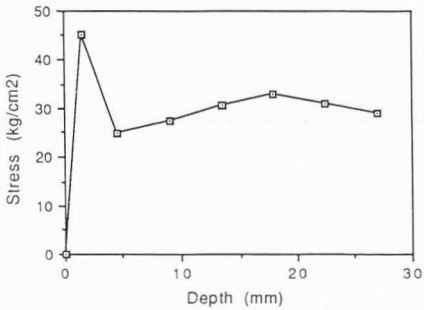

Fig. 26. Hardness of raw potatoes.

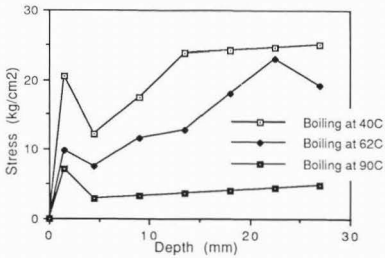

Fig. 27. Hardness of potato treated by boiling water at stage 1, 2 and 3.

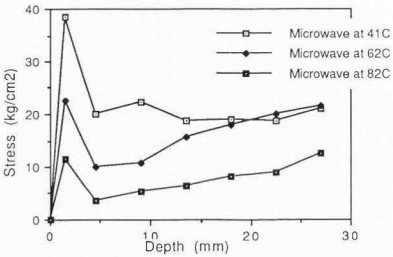

Fig. 28. Hardness of potato treated by microwave at stage 1, 2 and 3.

hardness of the center regions generally did not change much until the center regions were heated to gelatinization temperatures.

Discussion

Goebel et al. (1984) studied the distribution of gelled, chalky and paste areas of wheat starch-water dispersions heated in beakers with microwave ovens and conventional ovens. They indicated that the gelled regions where granulation first occurred were the inner regions of the microwave samples and the outer regions of the convection samples. Contrary to this report, we found that the coalescence of starch grains occurred in both inner and outer regions of the microwave samples. Nevertheless, the gelatinization did first occur in the outer region of the conventional samples. During normal cooking in boiling water the heated potatoes at stage 1 primarily consisted of unswelled starch granules. Only some outer regions contained swelled starch granules (Figs. 2-4). However, in microwave heated samples, the starch granules in both outer and inner regions had a similar appearance when they were heated to 40C (stage 1) (See Figs 11-13). At temperatures which caused gelatinization (stage 2), gelatinization occurred in both inner and outer regions with microwave heated potatoes (Figs. 14-16). No apparent structural differences were found between outer regions and center regions at stages 2 and 3 with microwave heating (Figs. 14-19).

There appears to be no consistent temperature gradient between the core and the surface of potatoes with microwave heating (Fig. 23). This suggests that the difference in starch granule swelling patterns could be closely related to different heating patterns between conductive heating and microwave heating. There are a number of reports on microwave heating patterns of potatoes. However, the conclusions were different. For example, Chen et al. (1971) demonstrated a temperature gradient from potato cores to peripheral regions with microwave heating and the opposite gradient for heating in boiling water. Conversely, Collins and McCarty (1969) reported a temperature gradient from the surfaces of potatoes to the cores instead of the core to the surface gradient shown by Chen et al. (1971). Therefore, further research needs to be conducted to clarify the issues of microwave heating patterns.

Turpin (1989) suggested that although conventional and microwave heating methods have the same objective, conduction heating has very different thermodynamic effects. With conduction heating, energy is added to the food molecules in the form of heat. With microwave heating, energy is added in the form of electromagnetic radiation, at a frequency of 2450 MHz and converts to heat at the target. Microwave heating of these samples took about one-tenth as much time as conduction heating to reach pre-determined temperatures (Table 1). It also explains the different starch swelling patterns and heating patterns between microwave and conductive heating.

Large intercellular spaces were evident with samples heated by both methods (Figs. 8-10, 14-19). However, the cell walls remained intact. The possible reasons for the prominent intercellular spaces are: 1) Granule shrinkage may have been due to increased packing density caused by gelatinization and retrogradation of the starch. 2) The intercellular spaces may have been created by partial solubilization of pectin in middle lamellas of cells which lead to easy separation of cells. Sefa-dedeh and Stanley (1979) reported that the greatest structural change of legumes during cooking was the breakdown of the middle lamella leading to the easy separation of intact cells. Nevertheless, they also stated that there was less evidence for the breakdown of the middle lamella in soybeans.

On the other hand, there was a marked difference in the appearance of starch granules between conventionally heated samples and microwave heated samples at stage 3. The starch granules from conventionally heated samples appeared to be more reticulated (Figs. 8-9) while the starch granules from microwave treated products tended to be more compact and dense (Figs. 17-19). This implies that conduction heating may hydrate more starch causing partial disruption of starch granules. Langton and Hermansson (1989) suggested that heat treatment of wheat starch dispersions gave rise to two stages of swelling and solubilization. Solubilization was observed in the center of granules during the first stage of swelling. Further swelling caused granule deformation and caused amylose release. Using an electron microscope, Buttrose (1963) concluded that acid caused corrosion of starch granules. Apparently, the heating treatment used in this study also caused the starch granule disruption (Figs. 8-9, 17-19). Nevertheless different heating methods resulted in different degrees of disruption. The microwave heated samples (Figs. 17-19) appeared to be less hydrated than the conventionally heated samples (Figs. 8-10). The microwave heated samples were less reticulated (Figs. 17-19).

Buttrose (1963) pointed out that starch

granules were made of concentric shells and were spherocrystals. This study showed that starch granules had a layered structure when they were heated to gelatinization temperatures (Figs. 7, 14-16). However, the layered structures were invisible when the temperature was above the gelatinization temperature (Figs. 8-9, 17-19).

The softening trends of conduction heated potatoes corresponded with heating patterns. In other words, softness increased following the increase of temperature (Figs. 20-22, 27). On the other hand, the softening trends of microwave treated potatoes at stages 2 and 3 could not be explained by their heating patterns while softening trends of microwave treated potatoes at stage 1 corresponded with the heating pattern (Figs. 23 and 28). This implies that softness does not solely rely upon temperature with microwave heating. Further investigations are necessary to elucidate the understanding of the relationship between softness, temperature of potatoes, and time exposed to microwave energy. Compared to conventionally heated potatoes, microwave treating did result in a little more moisture loss (Figs. 24-25). However, the relationship between hardness of heated potatoes and their moisture losses seems to be indistinct.

The findings in this study suggest that microwave heating may be more desirable for commercial products than conventional heating because of density. Moledina et al (1978) suggested that round and dense granules were desirable when economy packaging and shipping is used. In addition, he pointed out that round and dense granules also lend themselves well to automatic mashed potato machines which are becoming popular in restaurants and institutions.

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Discussion with Reviewers

Reviewer I: Were the boiled samples placed in plastic bags to prevent the introduction of additional water into the cells?

Authors: No. We purposely heated the samples with boiling water so that water in the samples would not evaporate. In this way we were able to study the impact of moisture loss on potato structure and softness between conventionally and microwave heated samples. Moisture loss was not evident with conventionally heated samples, but was evident with microwave heated samples.

Reviewer I: Why does Figure 14 look so different from the other micrographs?

Authors: Figure 14 shows the center region of a microwaved sample heated to 66C. In general, potato starch gelatinizes at about 62-65C. The characteristics of starch granules in Figure 14 indicate that starch gelatinized but did not completely coalesce. This phenomenon does not last long. These physical changes in starch take place rapidly thus they are not normally seen.

Reviewer I: J. Grider